Characterization of errors and Optimization of NDCX-II

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MON-303

HIF2010 Symposium

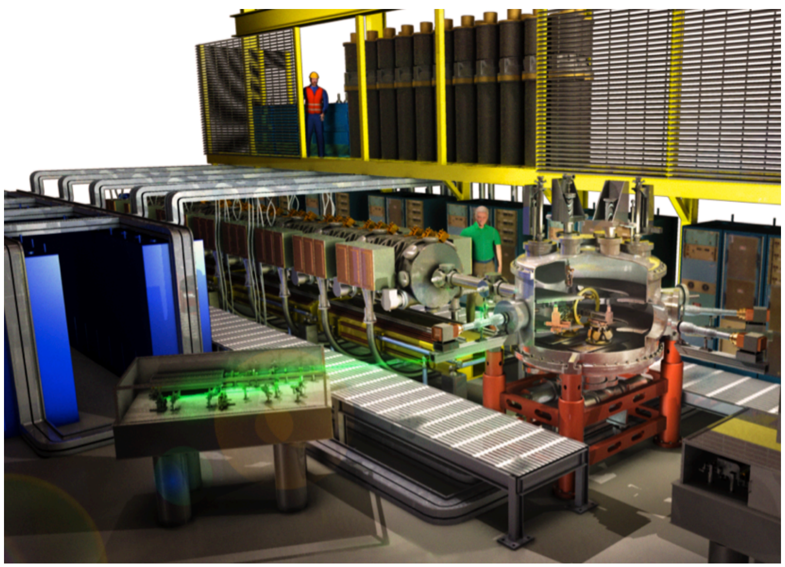
Outline

- Overview of NDCX-II
  - Design and simulations
- Figure of merit for optimization and error tolerance
- Errors and optimization
  - Final focus solenoid strength
  - Timing jitter
  - Solenoid errors
- Conclusions and summary

NDCX-II is underway at LBNL!

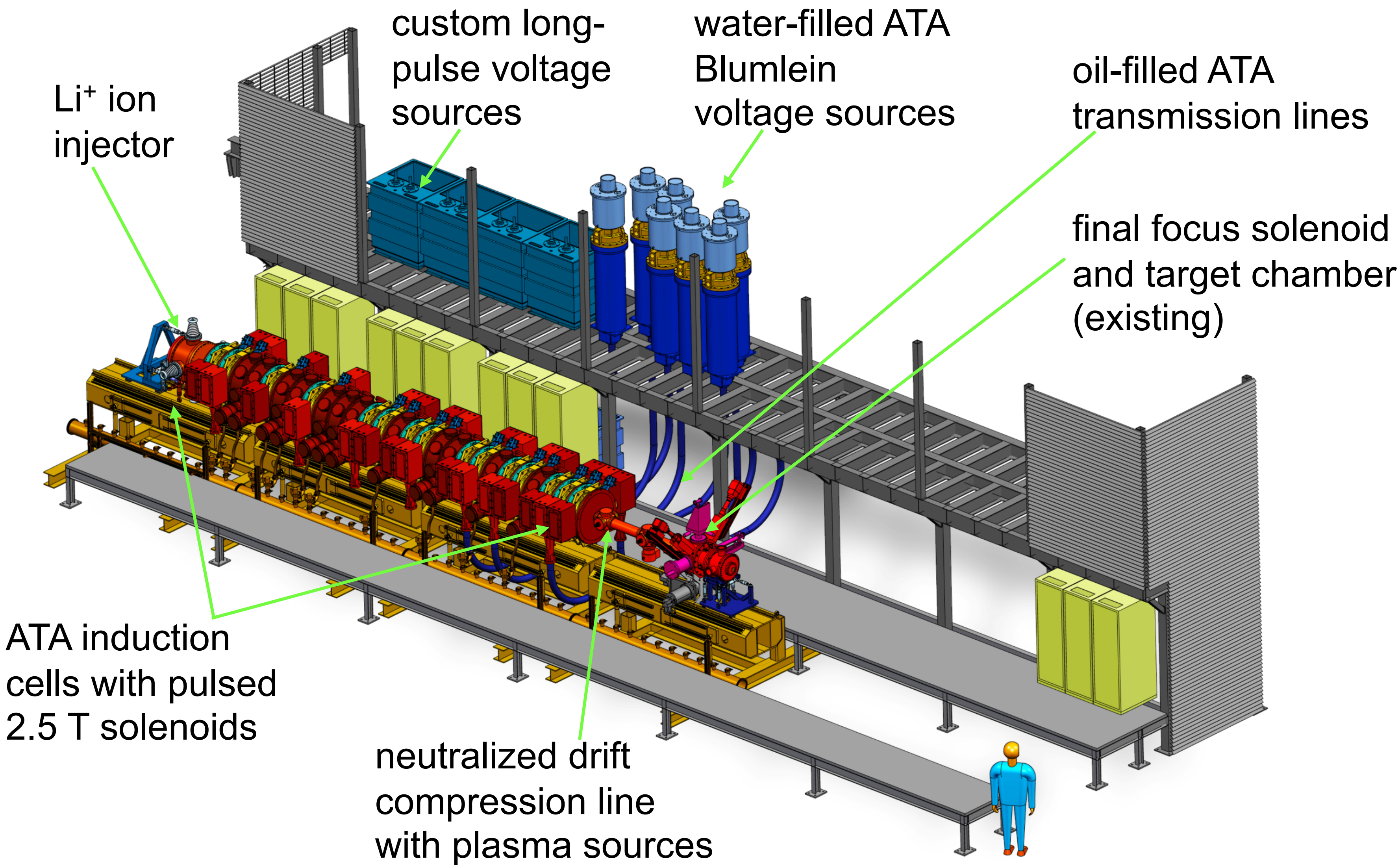
- DOE's Office of Fusion Energy Sciences approved the NDCX-II project earlier this year.

- $11 M of funding was provided via the American Recovery and Reinvestment Act ("stimulus package").



- Construction of the initial configuration with 15 +/- 3 cells began in July 2009, with completion planned for March 2012.
- Commissioning is to be in two 6-month phases.
- We hope to start target experiments in ~ October 2012, as we prepare for the second phase commissioning.

NDCX-II principal systems

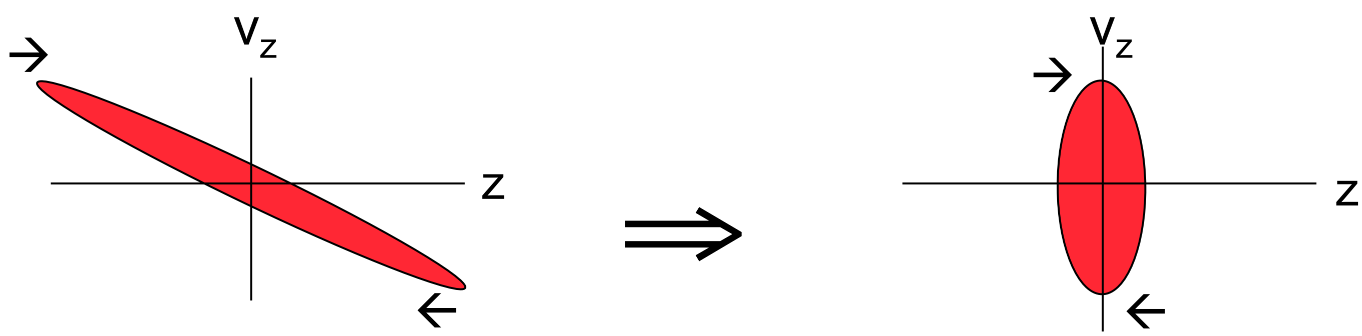


The baseline employs 12 active induction cells; we will apply any unused contingency funds to expand the scope

	NDCX-I (bunched beam)	NDCX-II construction project			NDCX-II 21-cell (enhanced)
		12-cell (baseline)	15-cell (“probable”)	18-cell (“possible”)	
Ion species	K^+ (A=39)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)
Total charge	15 nC	50 nC	50 nC	50 nC	50 nC
Ion kinetic energy	0.3 MeV	1.2 MeV	1.7 MeV	2.4 MeV	3.1 MeV

The “drift compression” process is used to shorten an ion bunch

- The process is analogous to “chirped pulse amplification” in lasers
- Induction cells impart a head-to-tail velocity gradient (“tilt”) to the beam
- The beam shortens as it moves down the beam line (pictures in beam frame):



Initial beam, with velocity tilt

compressed beam

- Space charge, if present, limits this compression
- To obtain a short pulse on target we introduce neutralizing plasma

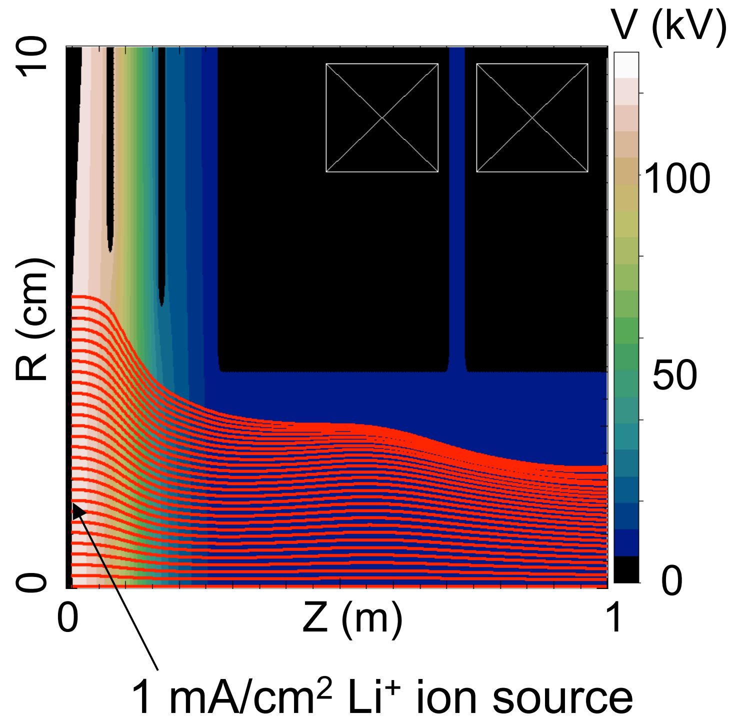
We employ the drift compression concept twice in NDCX-II

- Initial (non-neutralized) pre-bunching, to shorten the pulse duration for:
  - better use of induction-core Volt-seconds
  - early use of ATA Blumlein power supplies (~70 ns limit)

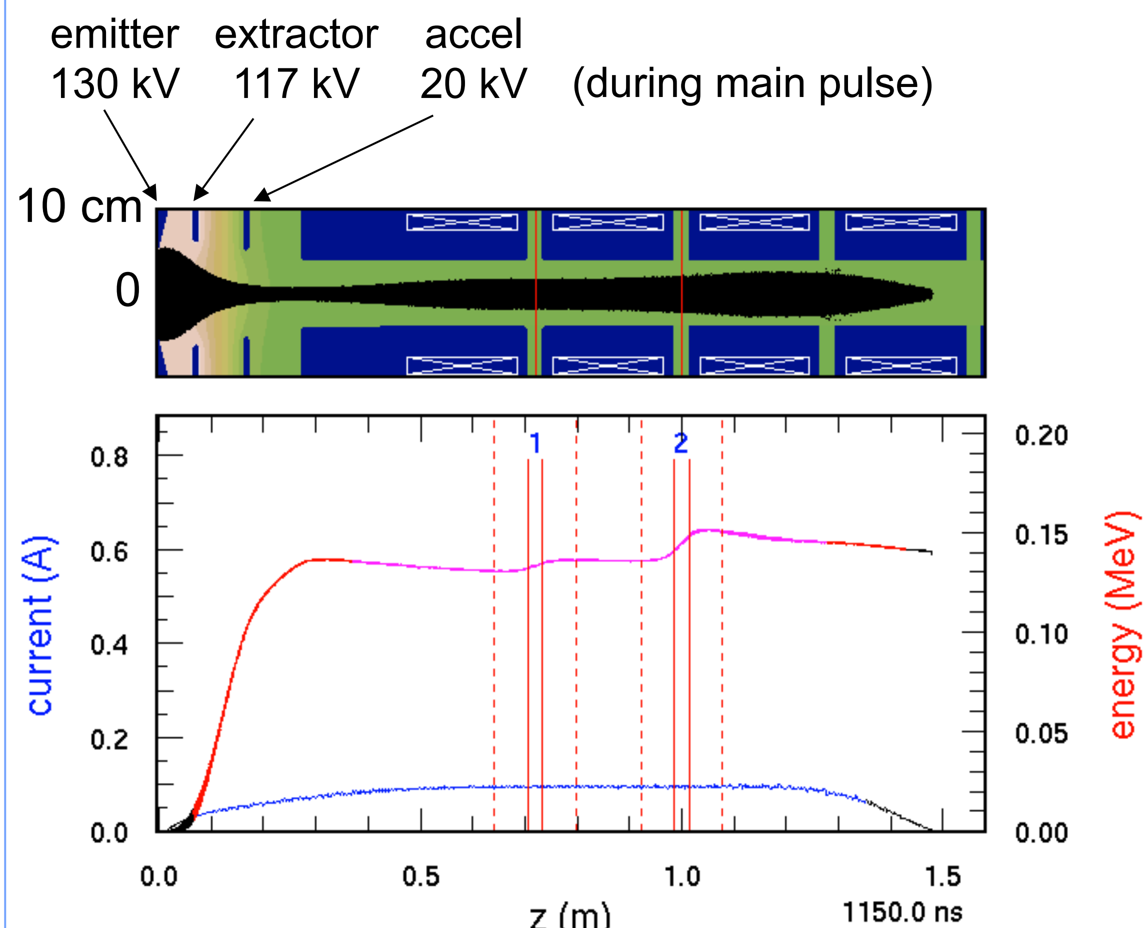
- Final “neutralized drift compression” onto the target
  - Electrons in plasma move to cancel the beam’s electric field
  - Require $n_{plasma} > n_{beam}$ for this to work well

Injector design was developed using Warp in (r,z) geometry

First, used steady-flow "gun" mode to design for a nearly laminar flow:



Second, carried out fully time dependent simulation:



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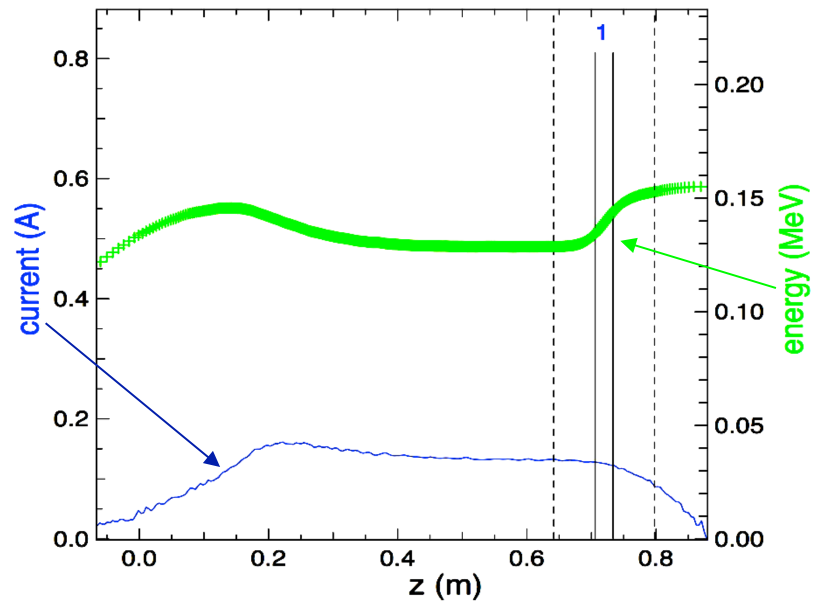
Basic accelerator schedule designed using the 1-D simulation code ASP ("Acceleration Schedule Program")

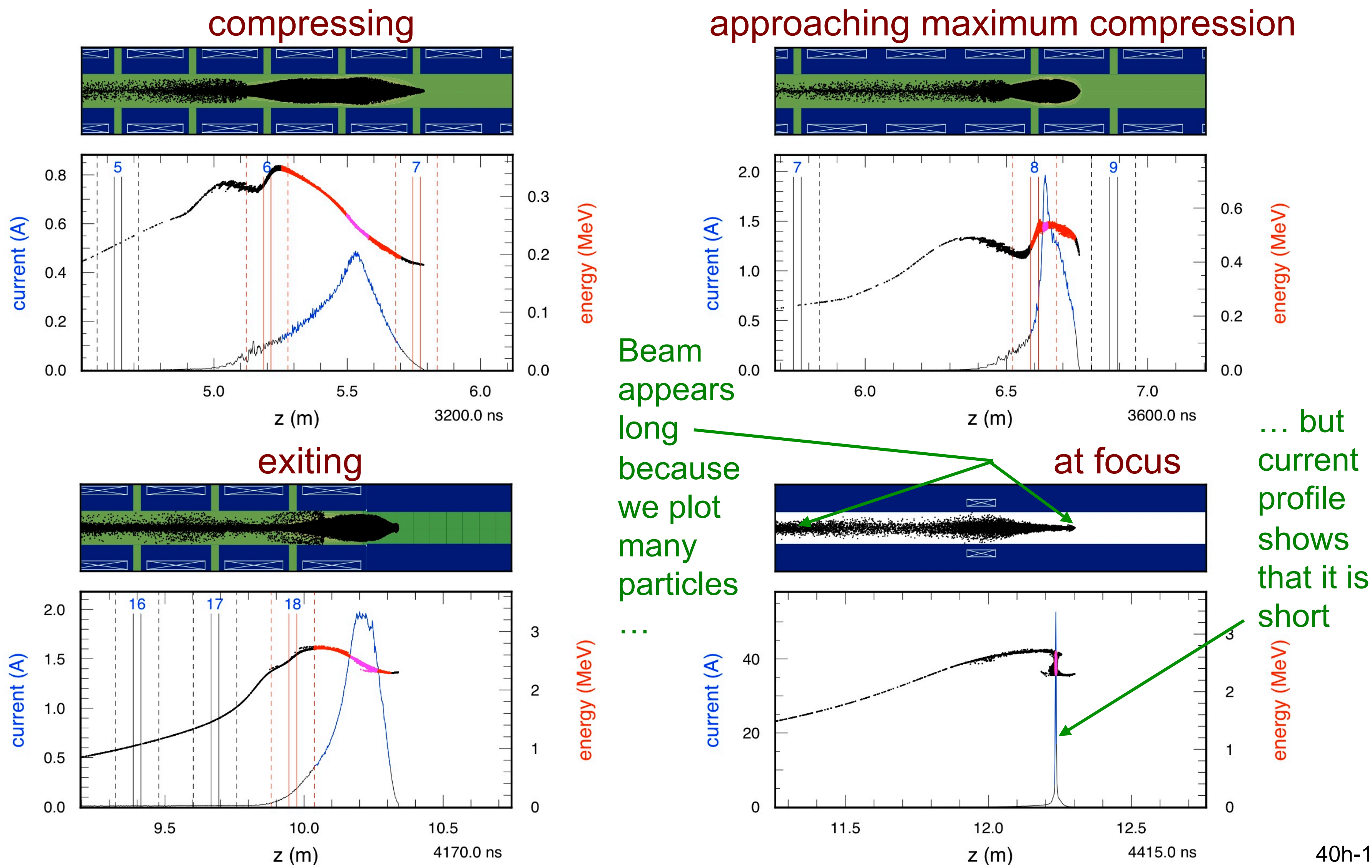
- ASP follows (z,v_z) phase space using a few hundred particles ("slices")
  - Includes longitudinal space-charge
  - Various models for accelerator waveforms

Example "Snapshots" of current and kinetic energy profiles vs. z, 120 ns into a simulated shot



- Centroid tracking for studying misalignment effects, steering
- Optimization loops for waveforms & timings, dipole strengths (steering)
- Interactive (Python language with Fortran for intensive parts)

Snapshots from a Warp (r,z) simulation (18-cell version), using design generated by ASP



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Potential sources of error in NDCX-II

- Solenoids:
  - Strength errors
  - Alignment errors, both offset and tilts
- Accelerating waveforms:
  - Timing jitter errors
  - Waveform errors, noise
- Source:
  - Waveform errors, noise
  - Non-uniform emission
  - Alignment errors
- Electrons (though not discussed here)
- Everything else

NDCX-II optimization

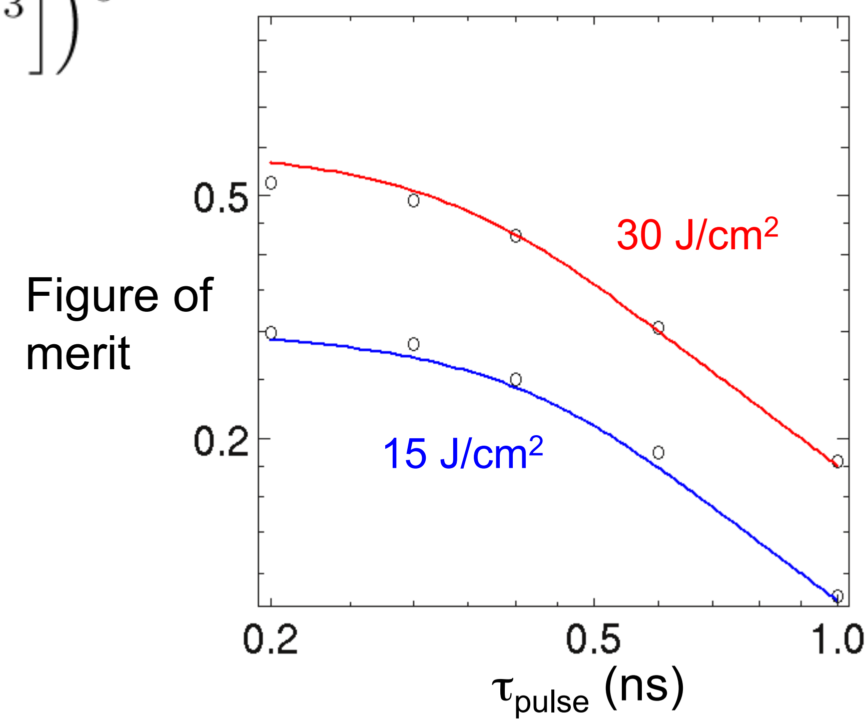
- Hardware layout is fixed
  - Source geometry (and voltage)
  - Number and arrangement of cells
  - Accelerating waveform shapes are fixed
- Variables
  - Timing of the waveforms
  - Transport solenoid strengths
  - Final focus solenoid location and strength
  - Target location
- Figure of merit
  - A measure of how well the beam drives the target, depends on beam energy, pulse duration and fluence on target
- Simulation approximations
  - Ideal plasma (though plan to simulate realistic plasma)

Figure of merit for error tolerance and optimization

- Figure of merit based on the beam energy, pulse duration and fluence on target
- It provides a measure of how well the beam will drive the target

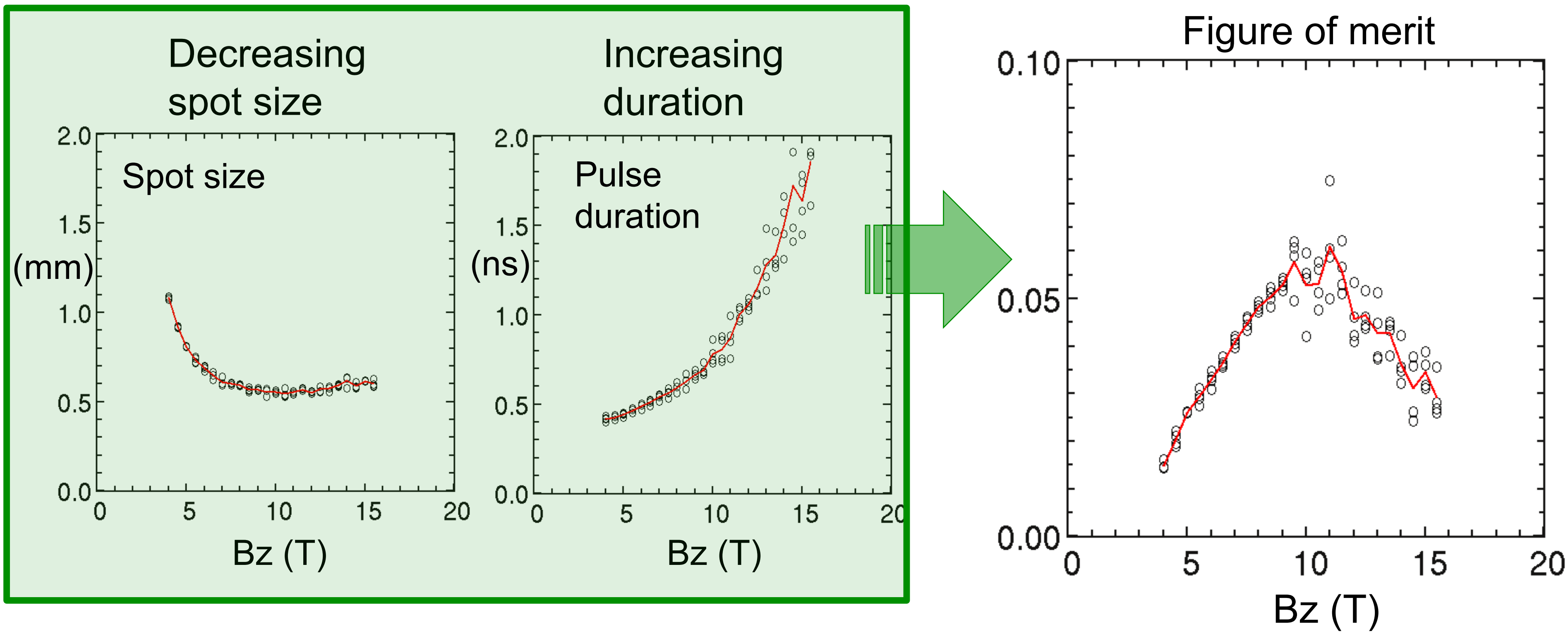
$$\tau_0 = (0.42 - 0.004f)(E/2.8)$$
$$P = 0.02f\left(\tfrac{2.8}{E}\right)\left(\tfrac{\tau_0}{\tau}\right)\left(1 - \exp\left[\left(\tfrac{\tau}{\tau_0}\right)^3\right]\right)^{\frac{1}{3}}$$

Here, f is the energy deposited in J/cm^2,
τ is the FWHM pulse duration,
E is the ion energy in MeV
τ_0 roughly approximates a scale time



Optimizing the final focus strength – not straightforward

- Figure of merit shows a peak with varying final focus Bz
  - Increasing Bz gives smaller spot size
  - But (surprise!) a longer pulse duration



Final focus confounds longitudinal compression

- Non-paraxial slowing down of particles in final focus solenoid is significant compared to pulse duration
- The axial velocity of a particle in a solenoid is approximately

$$v_z \approx v_0(1. - \frac{r^2\omega_c^2}{8v_0^2})$$

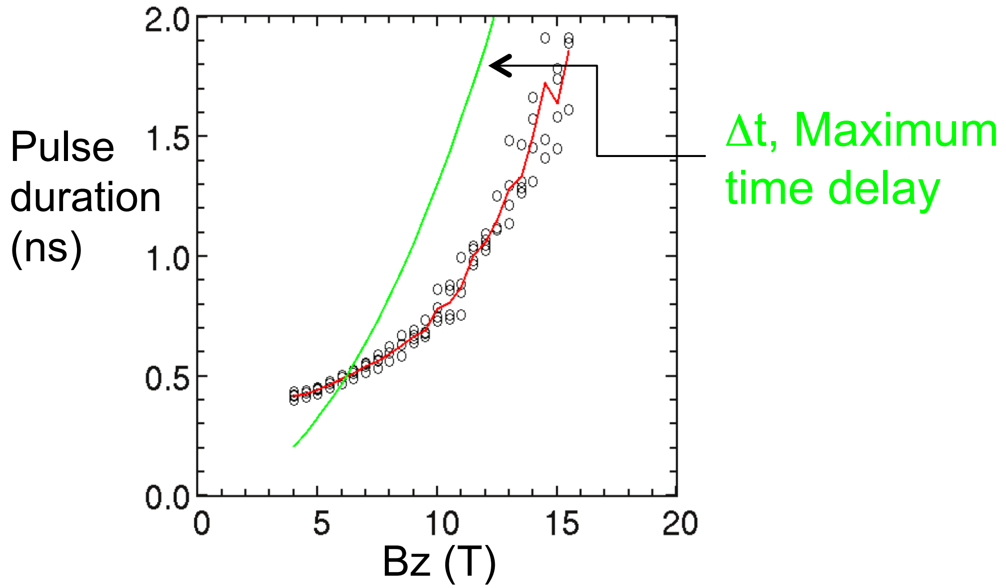
- Where v_0 is the initial velocity, r the particle radius, ω_c the cyclotron frequency = eB/m
- The particles at the outer edge of the beam see the largest delay, which is given by

$$\Delta t = \frac{La^2\omega_c^2}{8v_0^3}$$

- Where L is the length of the solenoid, and a the beam radius

NDCX-II 12 cell design example

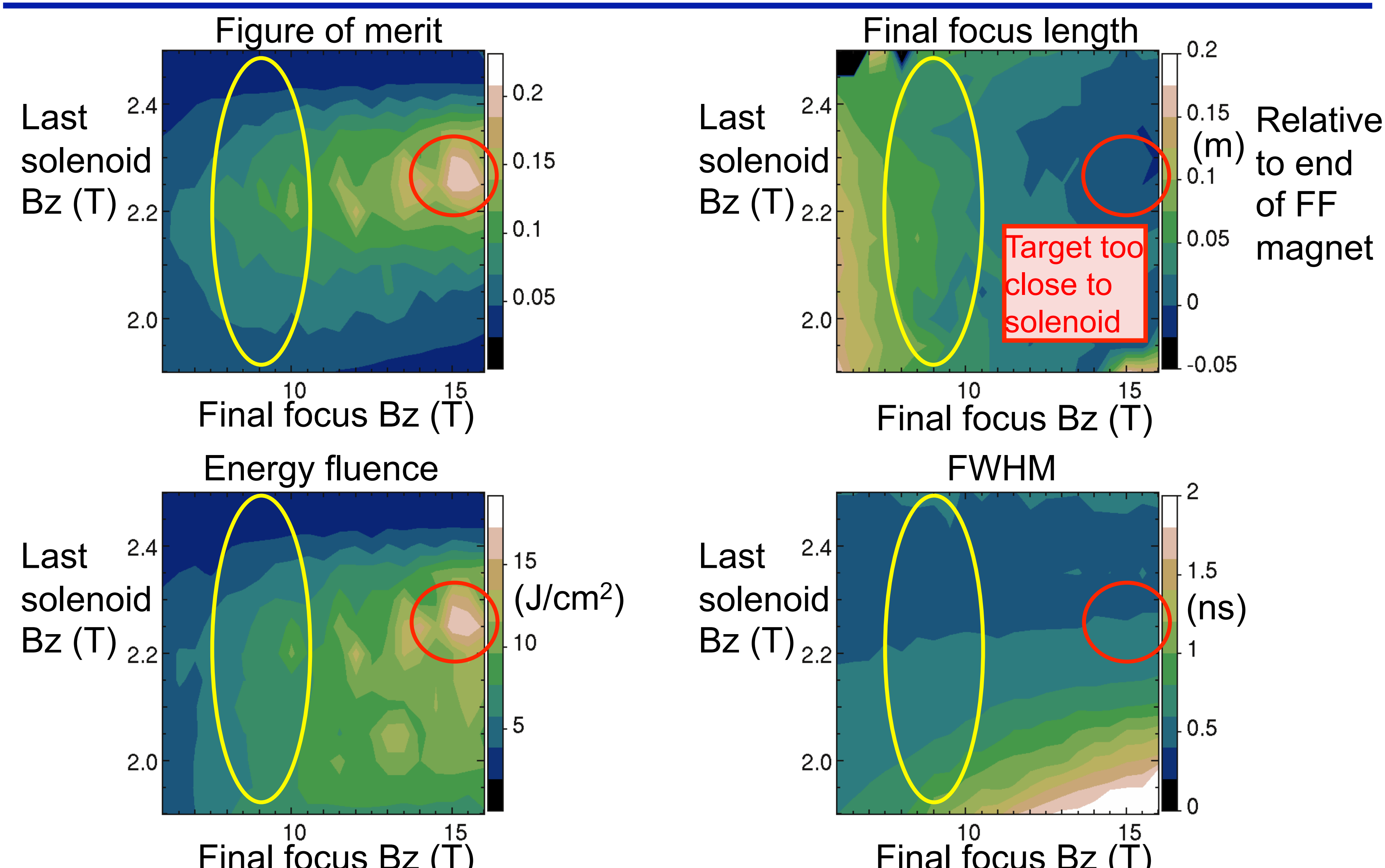
- Typical values
  - a = 2 cm
  - L = 10 cm
  - v_0 = 4.2e6 m/s
  - B = 8 T
  - Giving a delay Δt = 0.8 ns
- At the exit of the solenoid, the pulse duration is ~ 2 ns – the Δt is a large fraction of that
- At ~13 T, Δt ~ 2 ns



Minimizing the confounding of compression

- Unfortunately, $\Delta t \sim LB^2$, so effect cannot be reduced by changing the length of the solenoid (while maintaining the same convergence angle)
- Unfortunately, decreasing beam radius decreases the convergence angle giving a poorer spot size, but there may be a trade-off

Minimizing the non-paraxial effect by minimizing the beam radius



Minimizing the confounding of compression (cont)

- Unfortunately, $\Delta t \sim LB^2$, so effect cannot be reduced by changing the length of the solenoid (while maintaining the same convergence angle)
- Unfortunately, decreasing beam radius decreases the convergence angle giving a poorer spot size, but there may be a trade-off

- Fortunately, $\Delta t \sim 1/v_0^3$, so the effect diminishes at higher energy

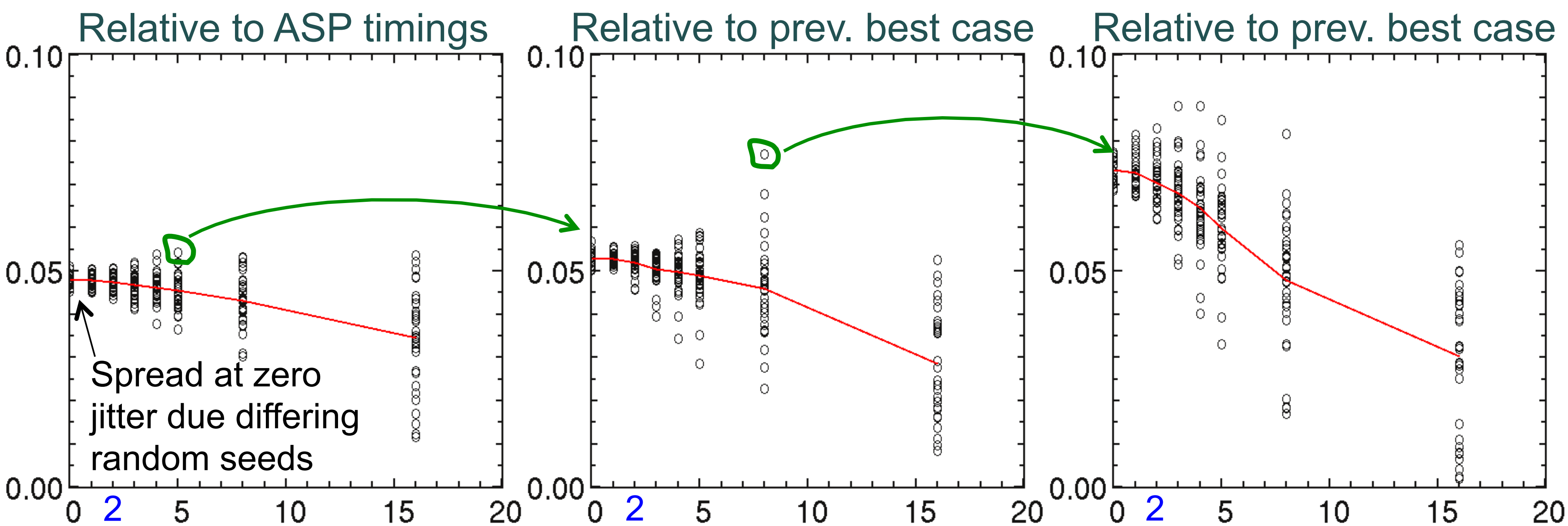
- Note that this effect is present in the transport solenoids, but the time delay is small compared to the beam duration and is further reduced by the compression ratio.

Optimizing timing of the waveforms

- The timings are originally setup with ASP simulations, but:
  - It has only an approximate description of the longitudinal self fields
  - It does not include transverse behavior and the final focus
- The timings are imported into Warp
  - The solenoids are adjusted to keep the beam nearly collimated
  - The location of the final focus can be optimized so the peak compression and focus are coincident
  - The peak compression will generally differ somewhat from the ASP results
- Optimal cases are sought using random searches or multivariate optimizer
  - The simulations are expensive – about 1 hour each
  - Needs a many parameter optimization (timing for each gap) and multivariate optimizers require many function evaluations

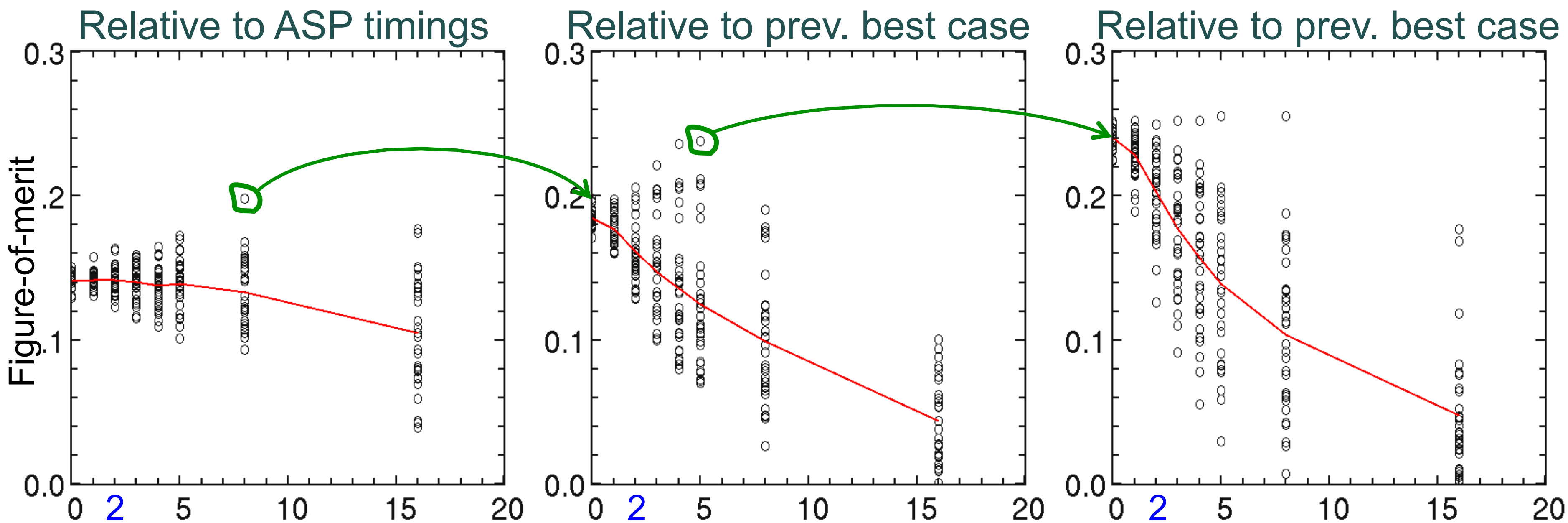
Ensembles optimizing 12 cell design

- Ensembles were carried out with increasing timing jitter
  - Shows sensitivity to timing jitter and possible improvement
  - The expected spark gap jitter is 2 ns



- Further cases showed little improvement
- Spread in results increases due to increasing sensitivity to initial conditions

Ensembles for 15 cell design – similar optimization path

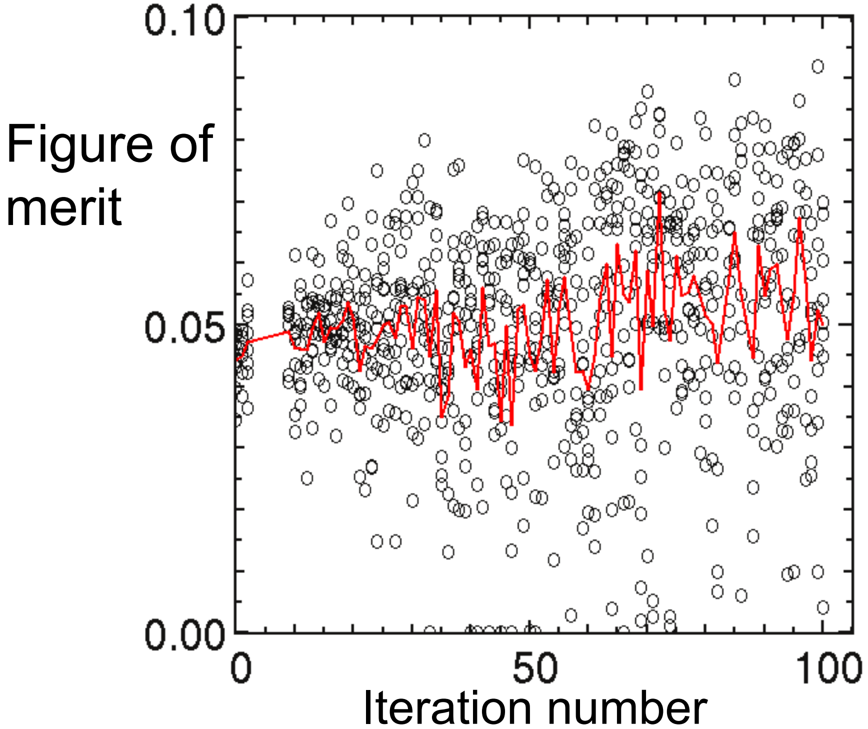


- Nominal NDCX-II spark-gap jitter is 2 ns
- Caveat emptor – better performance can be found using this optimization, but designs become less robust to jitter

Example, 12 cell with multivariate optimization

- A genetic optimizer (call Evolution) was used, using 8 cases per generation
- But, too many parameters (12 cell timings) so process was mostly random, but did turn up a good case

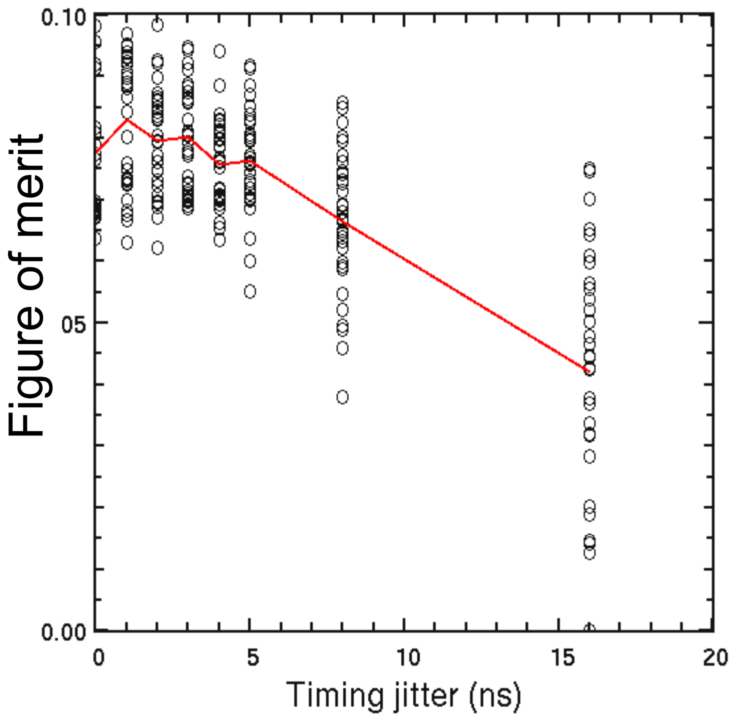
This shows the evolution of the figure of merit. The red curve, the average, does show slight increase, but best cases are mostly found randomly. The number of simulations was comparable to the random optimization, but a somewhat better case was found. However…



Example 12 cell with multivariate optimization, cont.

- The case that was found seems very sensitive to the initial conditions

Note the large spread for the case with no jitter (where spread is entirely due to particle random number seed.



Further optimization

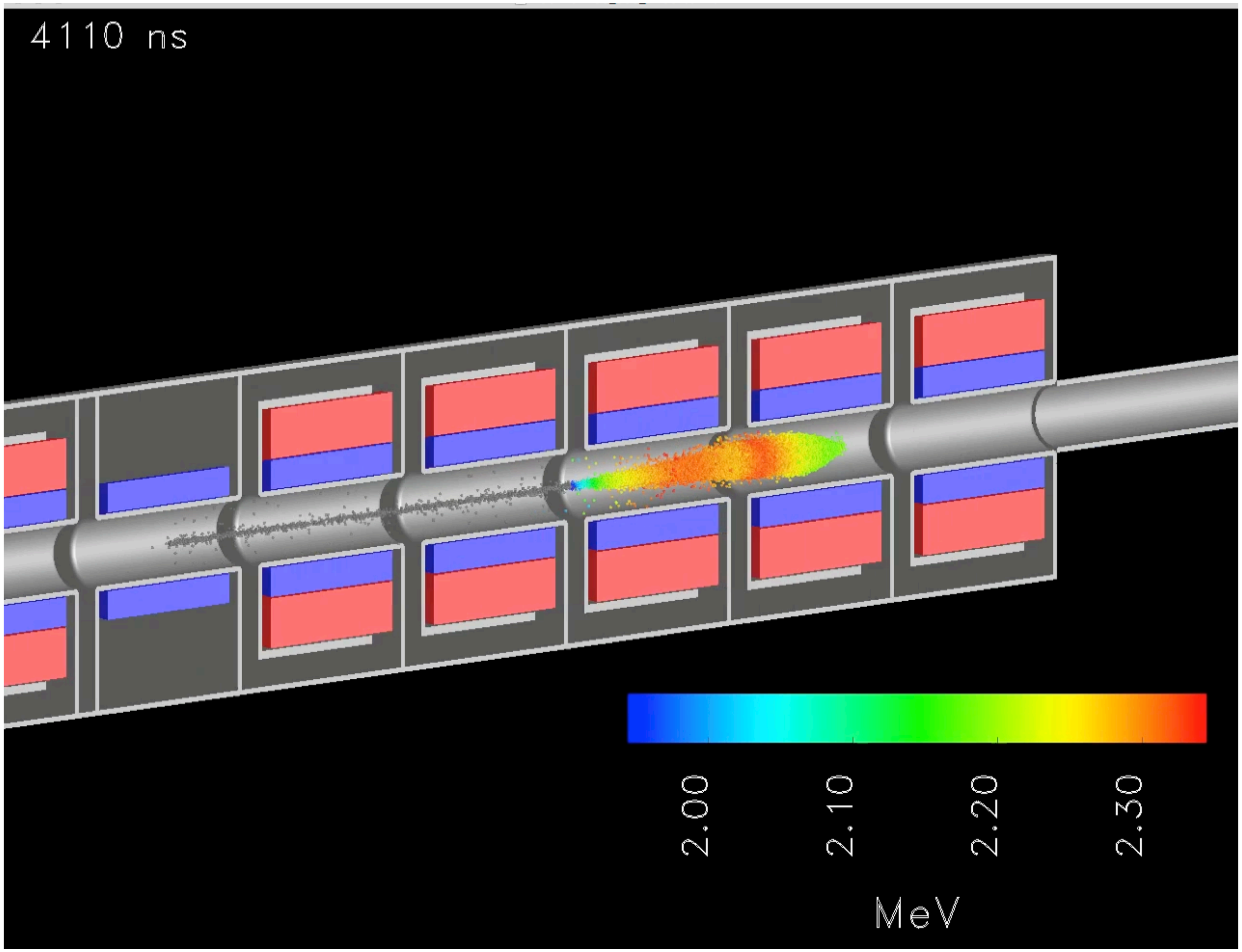
- The transverse size of the beam couples to the longitudinal behavior, so changing beam radius (by adjusting transport solenoids) may offer some further leverage for optimization (maybe by giving a nicer longitudinal profile).
  - Optimization complicated by other effects, e.g. non-paraxial pulse stretching, offsets
  - Optimization would be difficult – there are many parameters.

Solenoid alignment errors

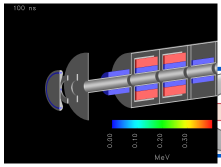
- Both solenoid offsets and tilts are included
- Error measure is the maximum displacement of the ends of the solenoid
  - Each end has different offset
  - Offsets chosen randomly from a uniform distribution

- At the very least, errors must be small enough to avoid beam scraping
- Would be good to keep beam near axis in final focus (to minimize non-paraxial pulse stretching)
- Would be better to keep beam centered on target
- Would be best to minimize degradation of spot size and shape

Video: Warp 3D simulation of 18-cell NDCX-II, with random offsets of solenoid ends by up to 2 mm (0.5 mm is nominal)

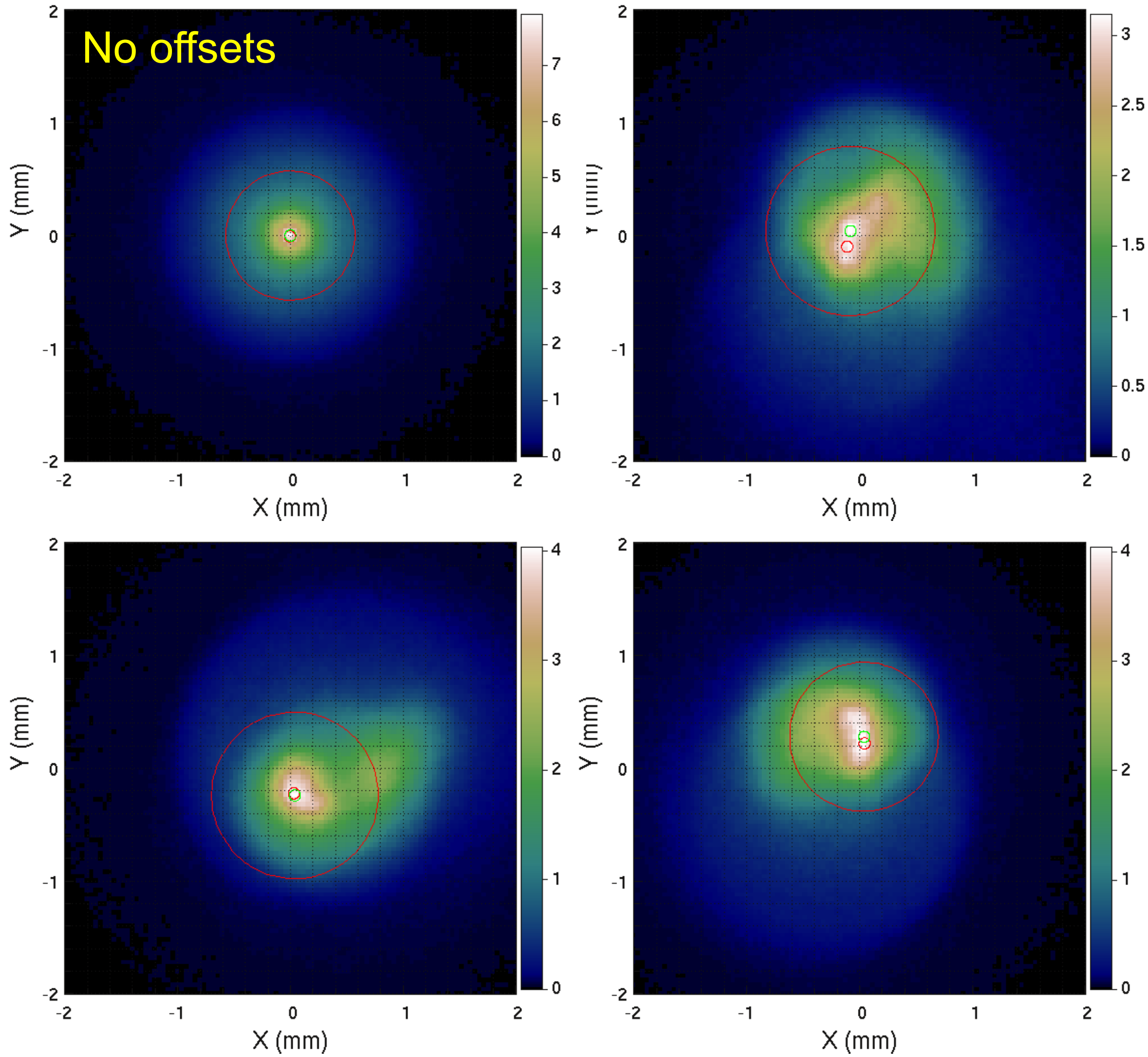


play video

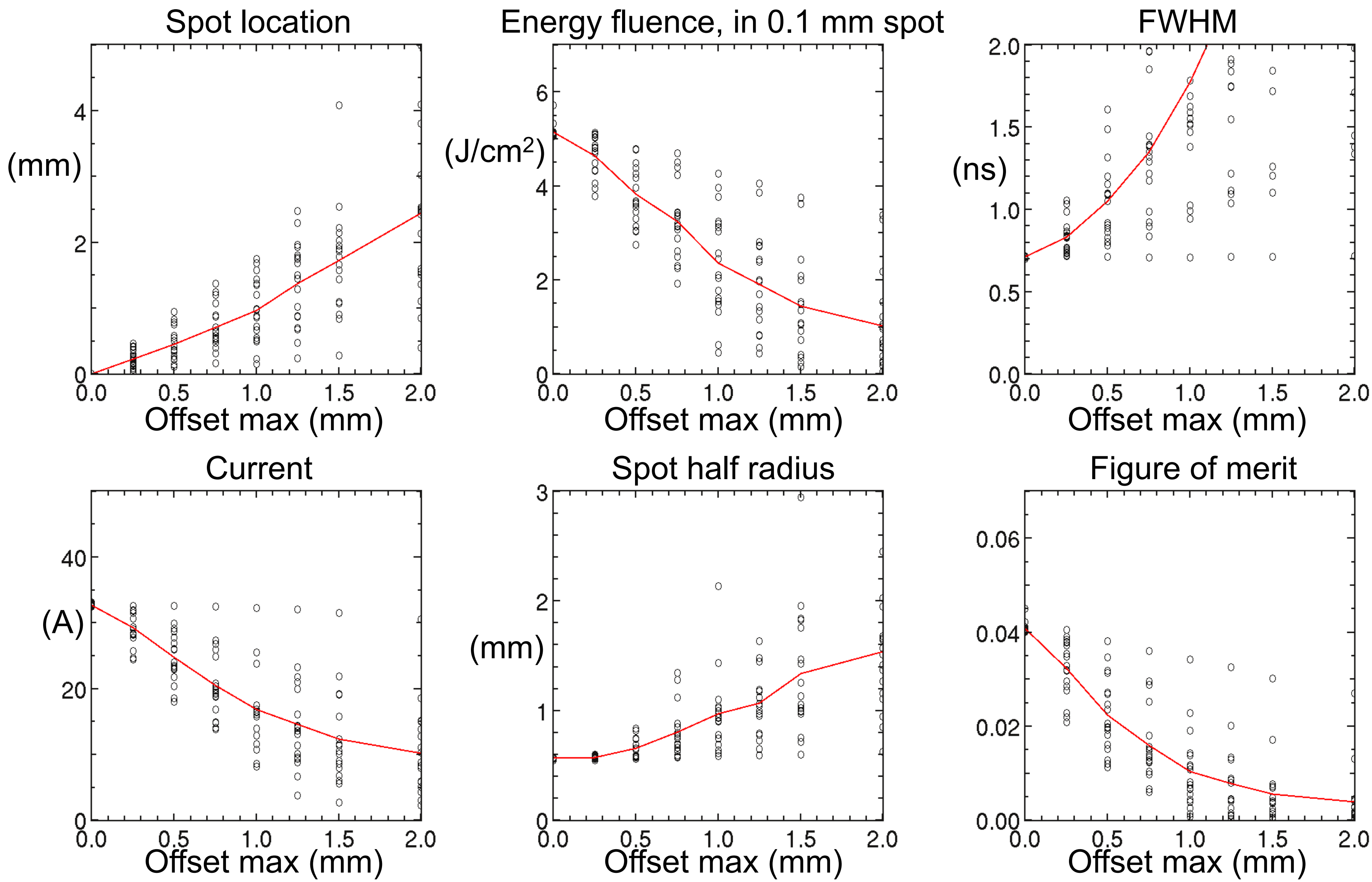


Example deposition patterns on target

- The beam deposition patterns for three different realizations of the solenoid offsets, with 0.5 mm max offset
- These give an idea of what distortions might be seen
- Red circle includes half the deposited energy
- Smaller circles, with 0.1 mm diameter, are at hot spots

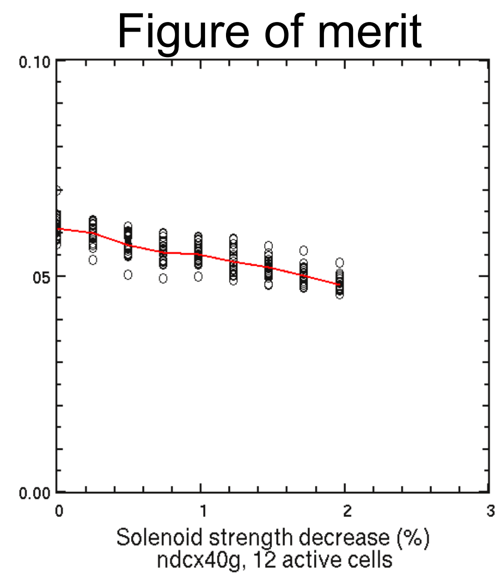


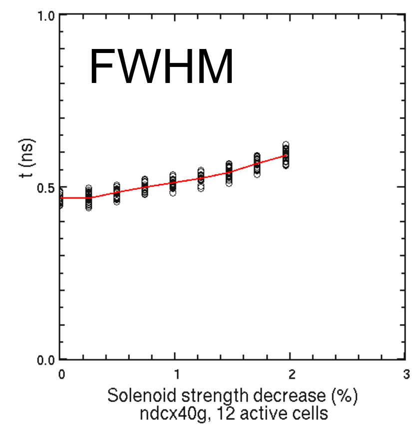
Ensembles with offsets – 0.5 mm acceptable (without steering)

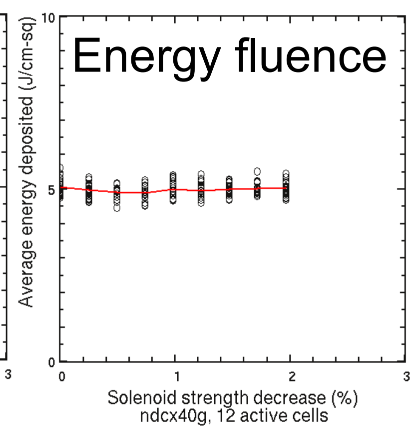


Solenoid errors due to varying magnet temperature

- With multiple shots, magnets heat up, increasing resistance and leading to a small decrease in field strength
- With all solenoids drifting the same amount, a 0.5% change seems acceptable
  - This gives a relatively small change in target performance
  - The figure of merit decreases with increasing solenoid strength since the beam radius is larger in the final focus solenoid, increasing the non-paraxial pulse stretching



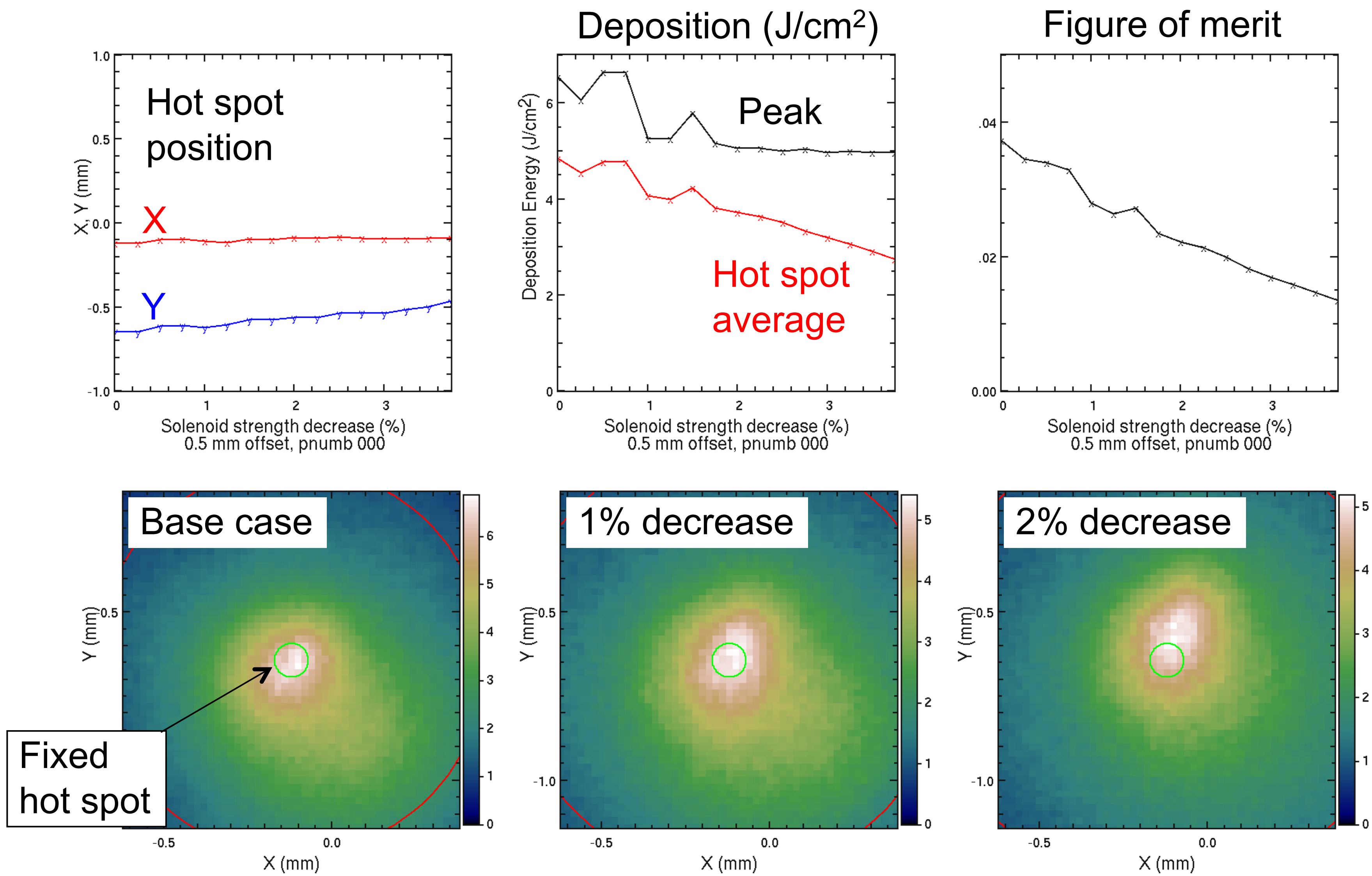




Solenoid strengths errors with offsets

- With both solenoid offsets and varying solenoid strengths, the location of the hot spot on target will drift
  - The size of the transverse offset kick in each magnet changes, changing the path of the beam centroid
  - The drift needs to be small enough so that the hot spot stays near the diagnosed spot on the target
- A 0.5% change in solenoid strength (with a max of 0.5 mm offset) seems reasonable
  - The hot spot drifts roughly 0.1 mm per % field strength change
  - In a 0.1 mm radius fixed spot, the deposited energy can decrease by as much as 10 to 15%

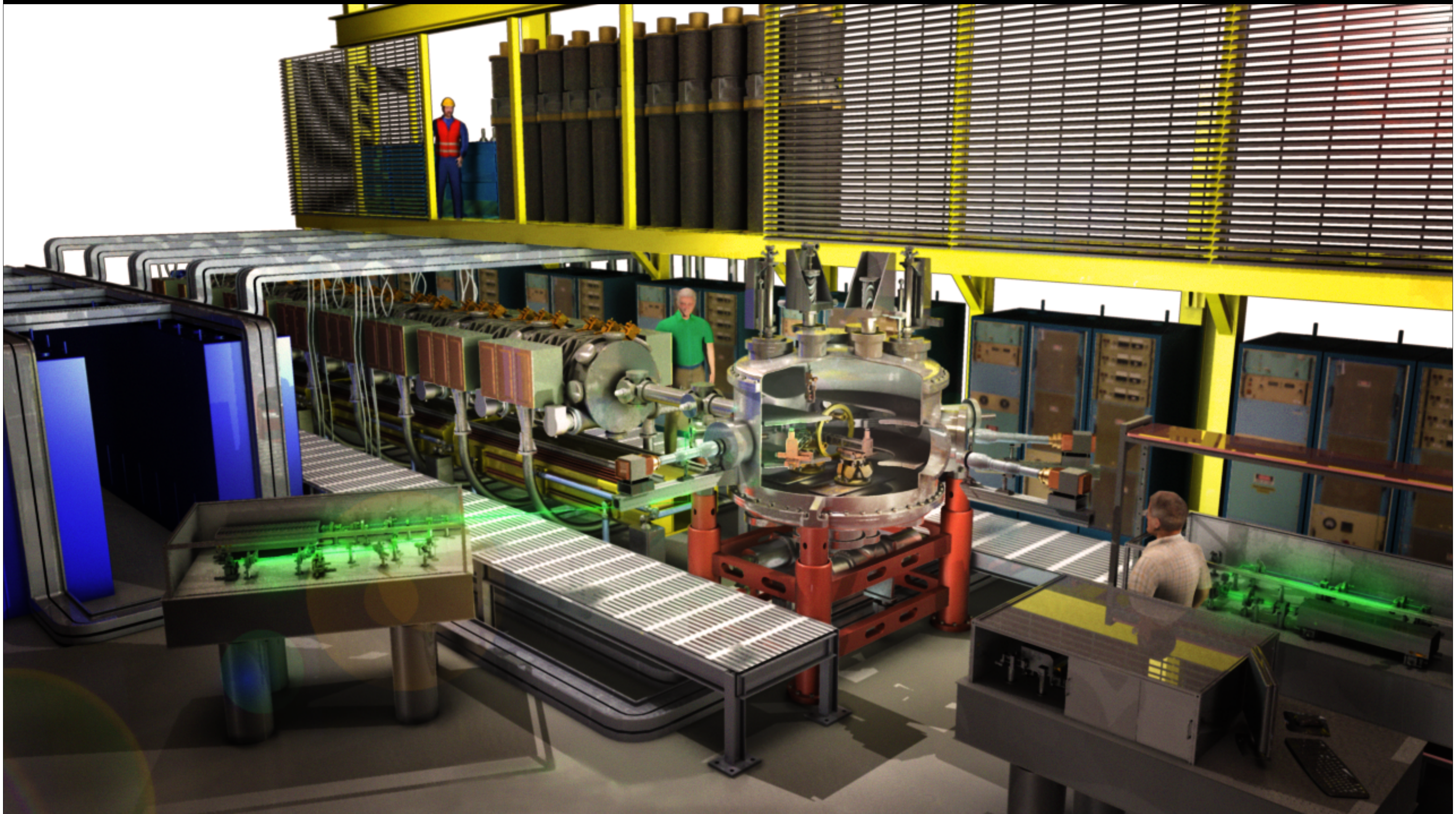
Solenoid strength error with offsets – sample case



Conclusions

- NDCX-II construction underway, but some areas open to further analysis and improvement
- The design is heavily dependent on simulation, using ASP and Warp
- Discovered a new effect, non-paraxial pulse stretching
  - Puts a constraint on the final focus solenoid strength
  - Complicates optimization by closely coupling longitudinal and transverse
- Analysis of error tolerances couples with optimization
  - Design is not completely optimized
  - Small “errors” can lead to improved designs
- Tolerances found:
  - Expected 2 ns timing jitter is well within acceptable range
  - 0.5 mm solenoid offsets tolerable (but steering would be nice)
  - 0.5% solenoid strength errors OK

Heavy Ion Fusion Science Virtual National Laboratory



NDCX-II Warm Dense Matter Research Facility